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Title: Nuclear Weapons Physics Made Very Simple

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Nuclear Weapons Physics Made Very Simple

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What makes an atomic bomb and how it works is presented with the help of film clips from several Hollywood actors in previously released films by the U.S. government. Basics of atomic reactions, fission, chain reactions, etc. are covered so that the novice weapon engineer will leave having a though understand on how an A-bomb works.

Nuclear Weapons Physics Made Very Simple

By
Dr. Glen McDuff
Presented to
Weapons Engineering Study Hall

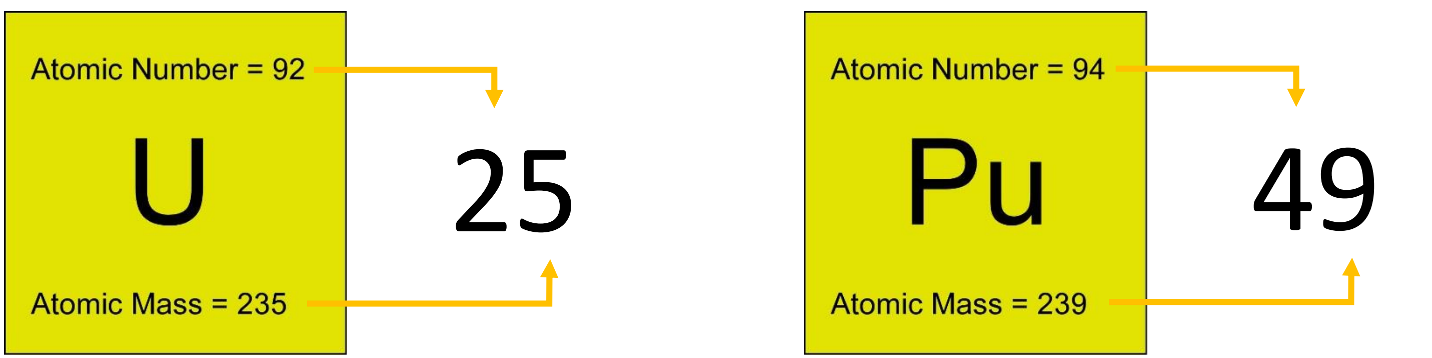
LAUR-18-XXXXXX

Nuclear Weapons Made Very Very Simple

- Topics to be covered:
- Nuclear Physics
- Fission Weapons Basics
- Materials
- Thermonuclear Reactions
- The First Weapons Development
- Current Weapons

Atomic Lingo

- Tuballoy or Tu, comes from the Tube Alloy Project in the United Kingdom, use to describe natural uranium, ^{238}U(99.3%) ^{235}U(0.7%) and sometimes depleted uranium , ^{238}U(99.8%)
- Oralloy, or Oy, comes from “Oak Ridge Alloy”, or enriched uranium that is, typically ^{235}U(>90%)
- Manhattan Code Names



Nuclear Weapons Made Very Very Simple

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- ***Nuclear Physics***
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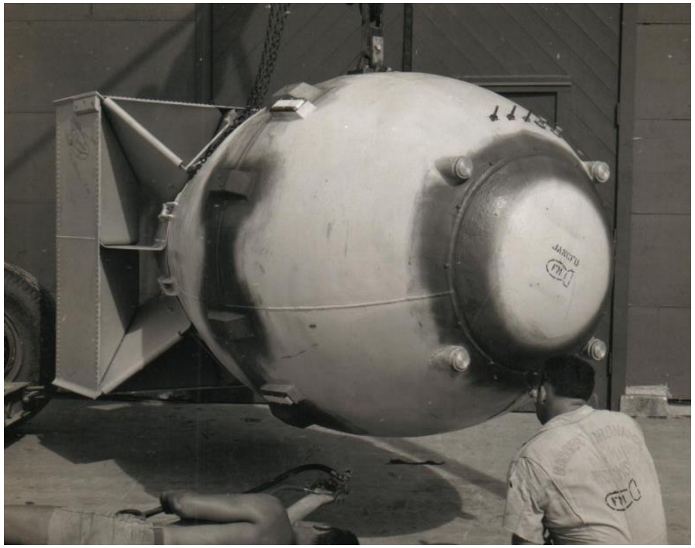
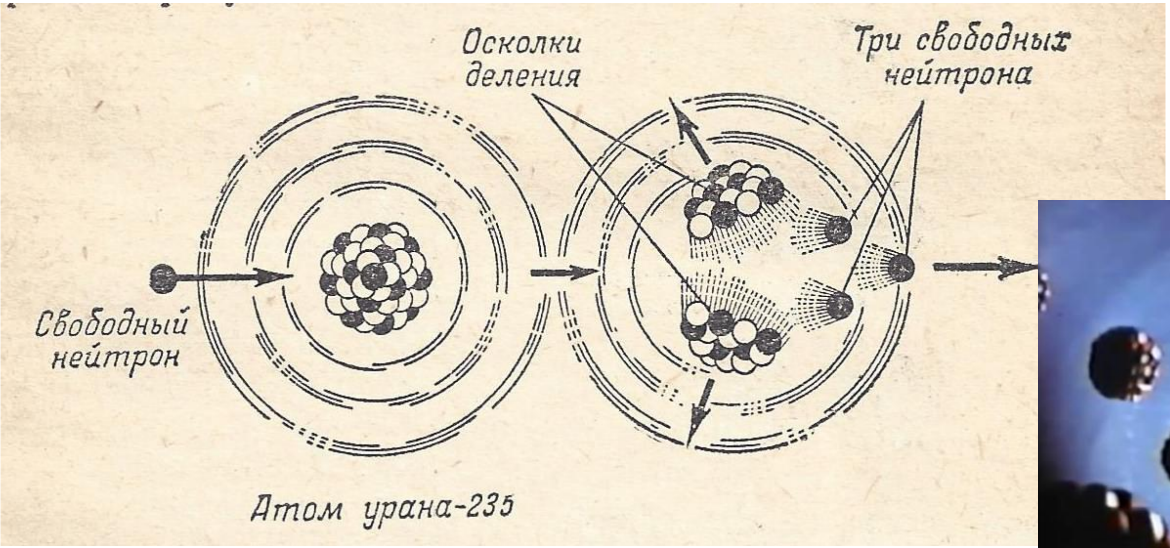
Nuclear Physics for A-Bombs

- Fission
- Energy Release
- Criticality



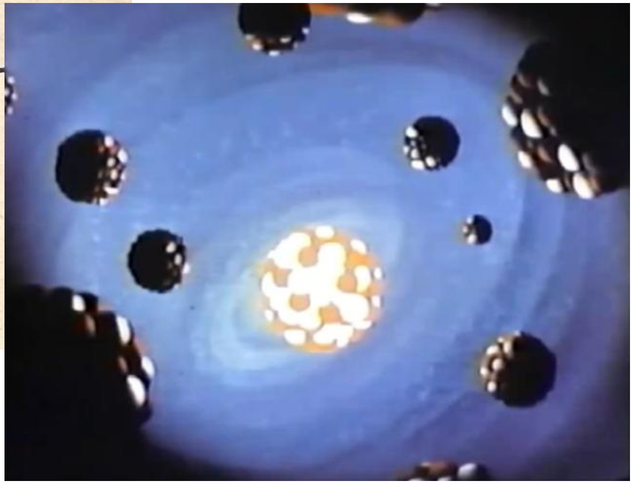
Fission – Neutron Induced

- There are several possible reactions when a neutron interacts with a ^{235}U nucleus, capture, scatter, & of course, fission
- Release of energy is in the form of electromagnetic, fission fragments and neutrons



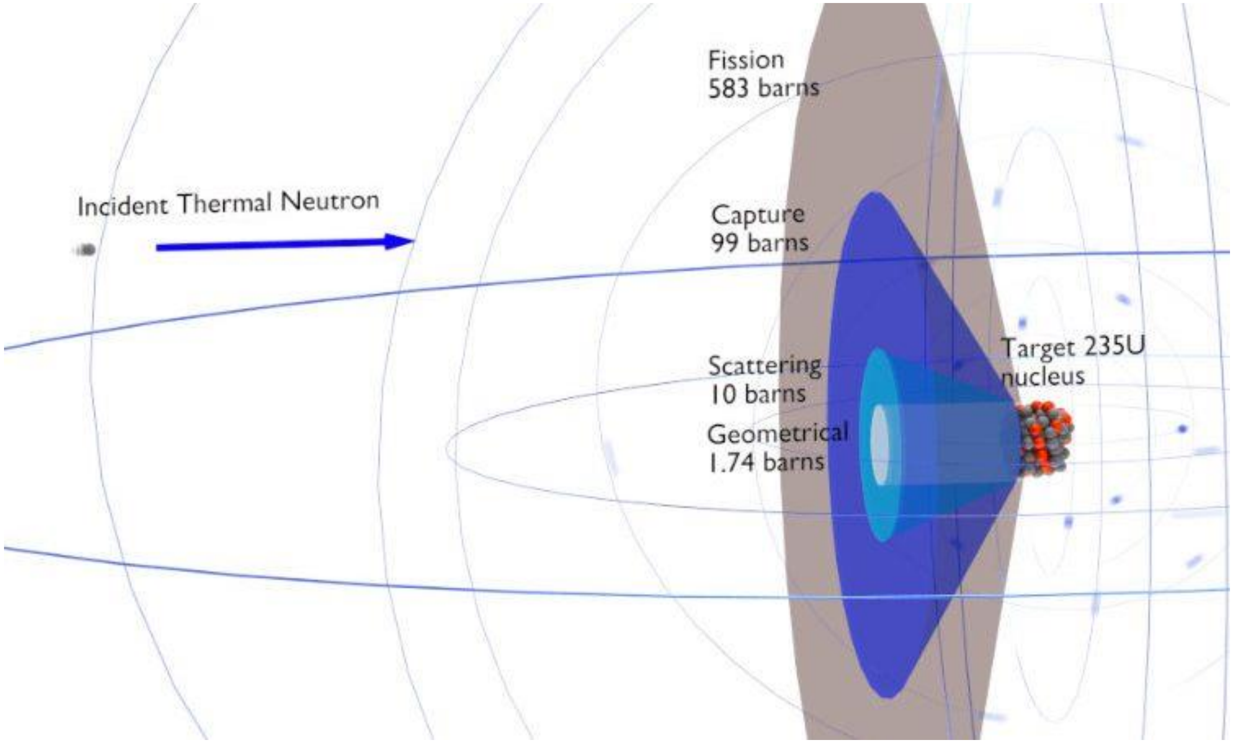
Atomic Weapons and Defense, Moscow, 1958

Average neutron energy ~2MeV

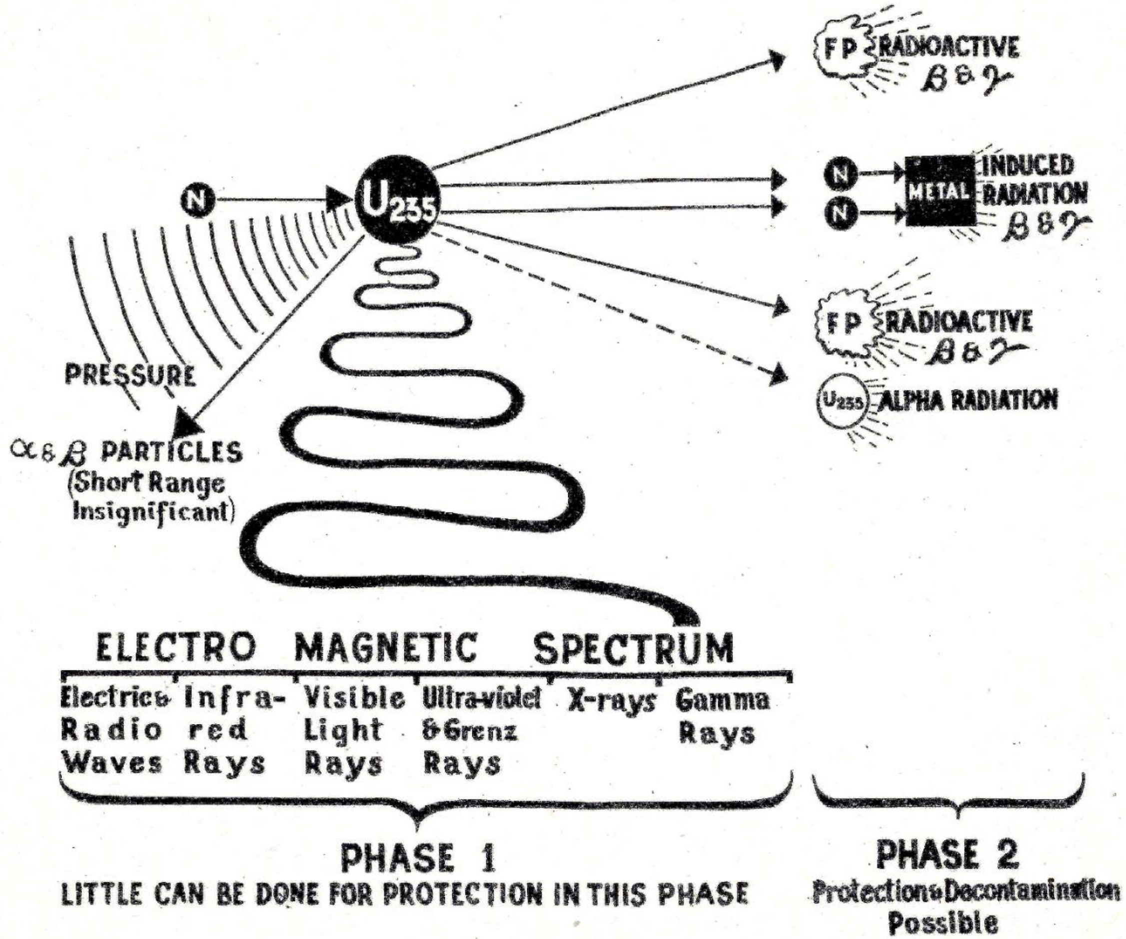


Cross Section or Probability of a Reaction

- The probability that two particles will collide and interact
- Typical reactions are: scattering, fission, absorption, etc.
- It's measured in barns (area), 1 b = 10^{-24} cm^2

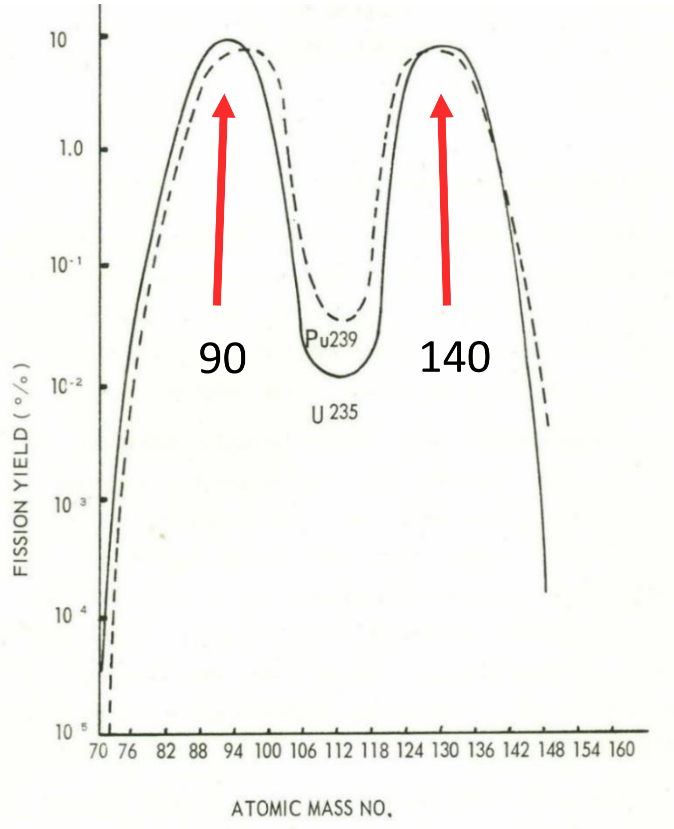


Fission Products



Fission Fragments

- Typical mass numbers of around 90 and 140
- This curve was called



Main Sources of Residual Radiation

Short lived
^{131}I
^{140}Ba

Few months
^{141}Ce
^{95}Zr
^{95}Nb
^{89}Sr

Couple of years
^{144}Ce
^{106}Ru
^{106}Rh
^{147}Pm

Several years
^{90}Sr
^{137}Cs

Finally
^{99}Tc

Fission Fragments

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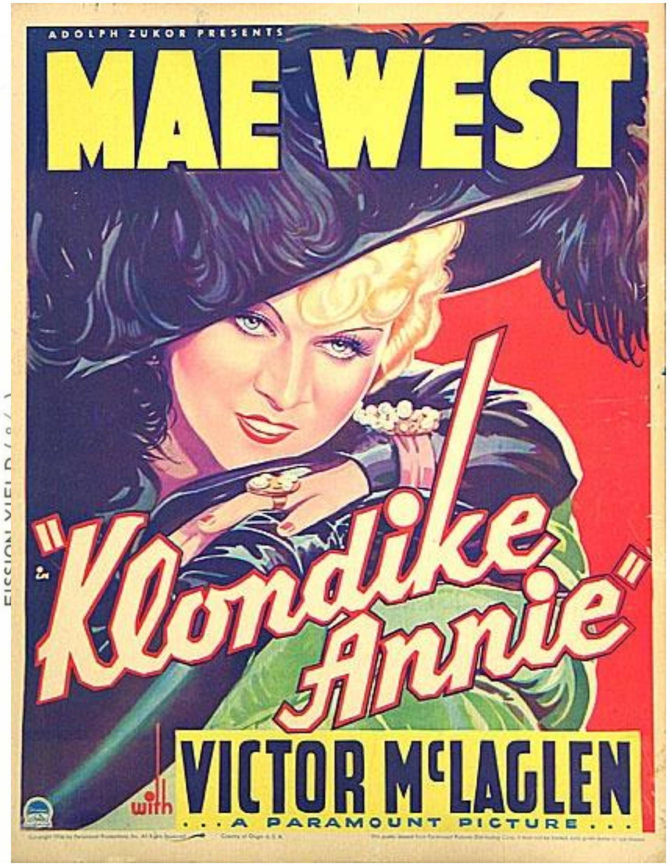

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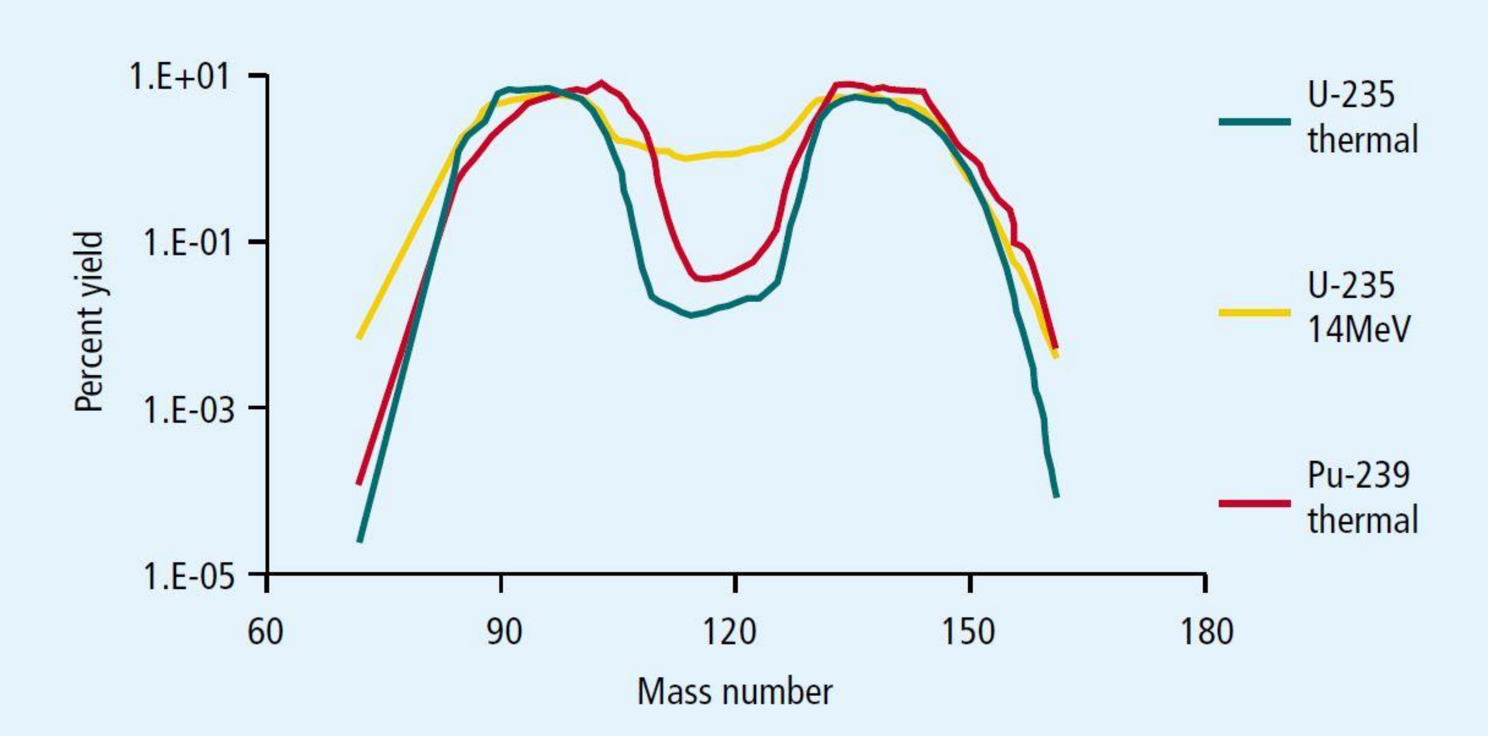
Couple of years
^{144}Ce
^{106}Ru
^{106}Rh
^{147}Pm

Several years
^{90}Sr
^{137}Cs

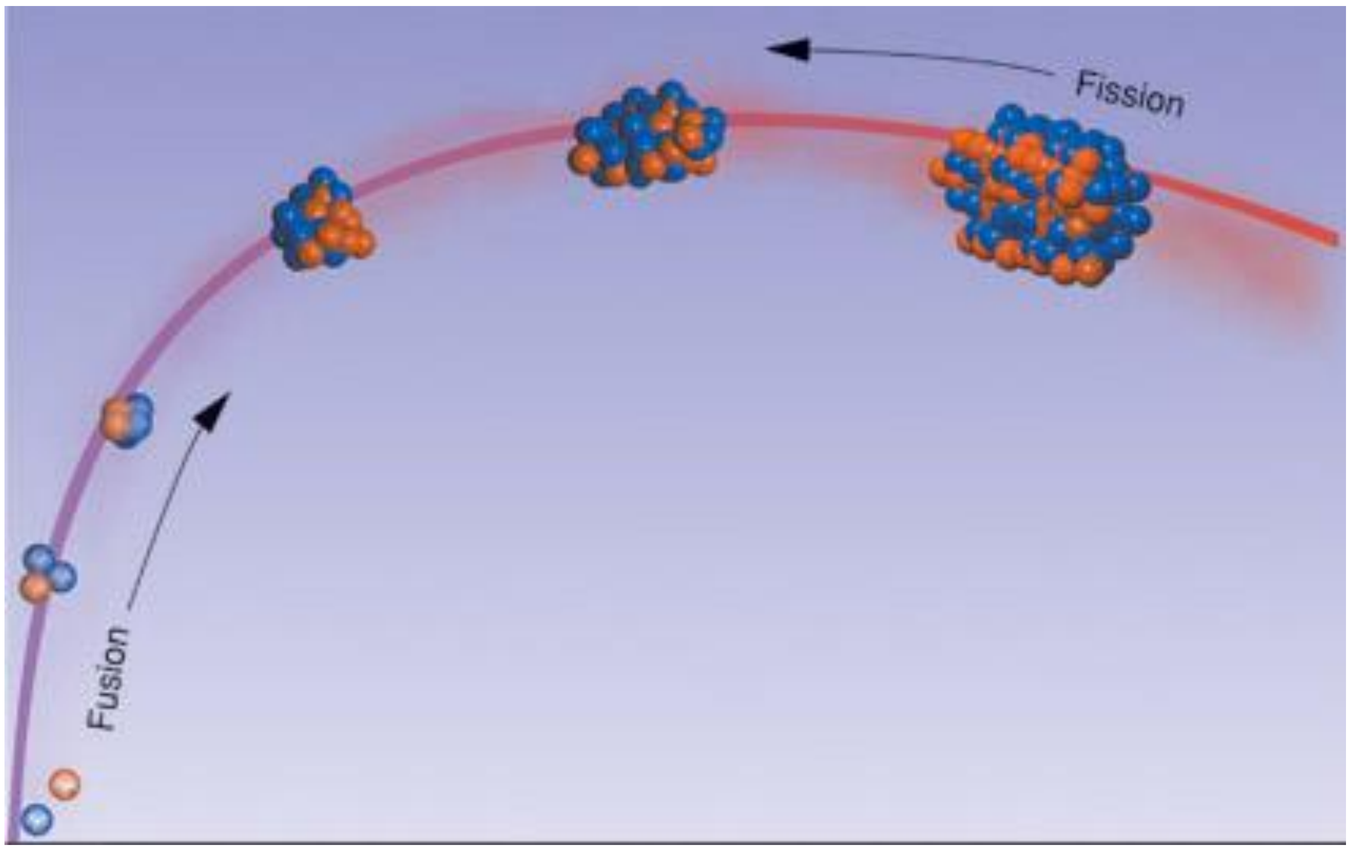
Finally
^{99}Tc

Fission Fragments

- Products are dependent on the material and the energy on the bombarding neutron



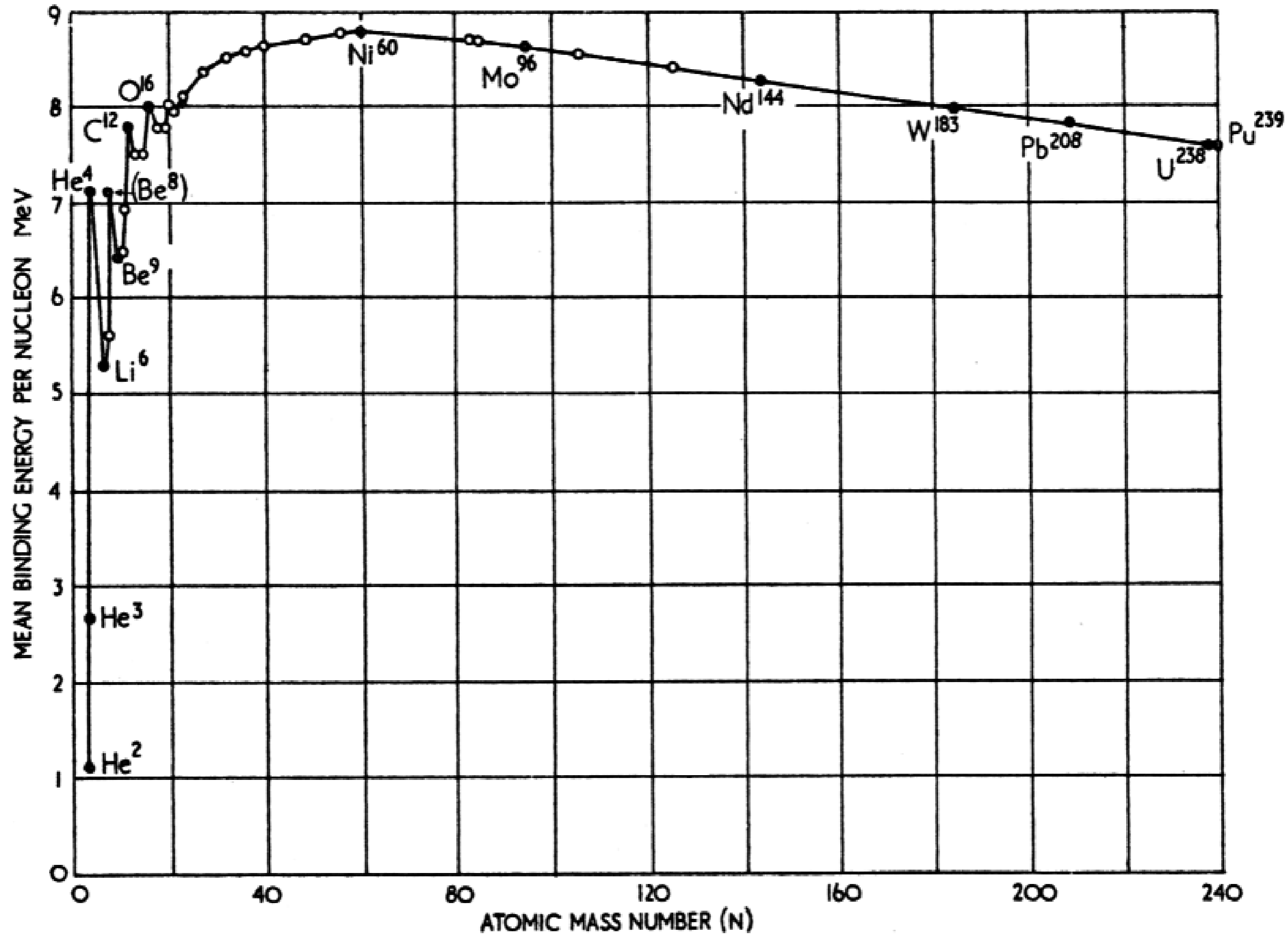
Energy Release and The Curve of Binding Energy



Average Binding Energy per Nucleon, MeV

Mass Number, A

Curve of Binding Energy



Energy Release in Fission

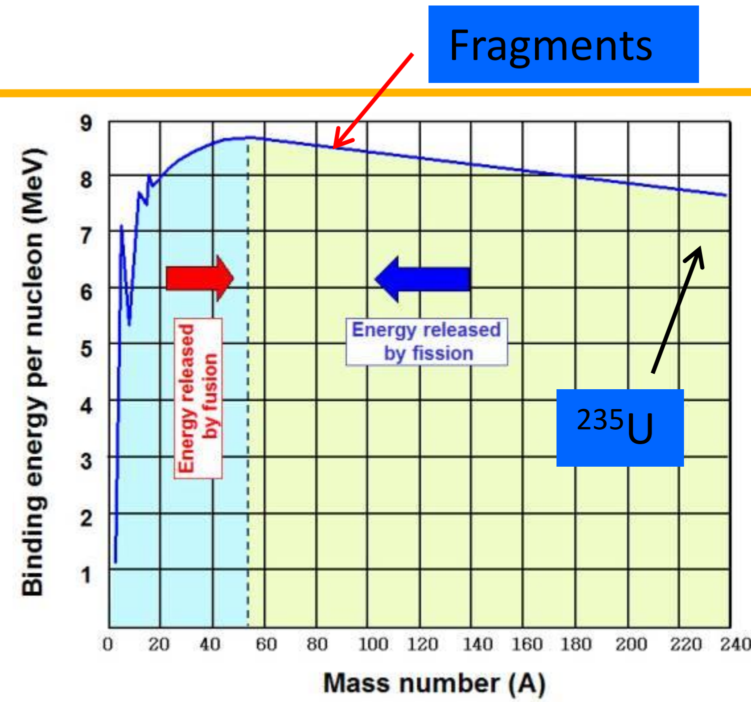
A typical fission reaction is

$^{235}U + n \rightarrow {}^{236}U \rightarrow 2\text{ Fragments} + 2n$

unstable totaling 234

$^{235}U + n$ = 236 nucleons with an average binding energy of 7.6 MeV/nucleon

giving 236 x 7.6MeV/nucleon = ***1793.6 MeV***



2 Fragments have 234 nucleons with an average energy of 8.53 MeV/nucleon

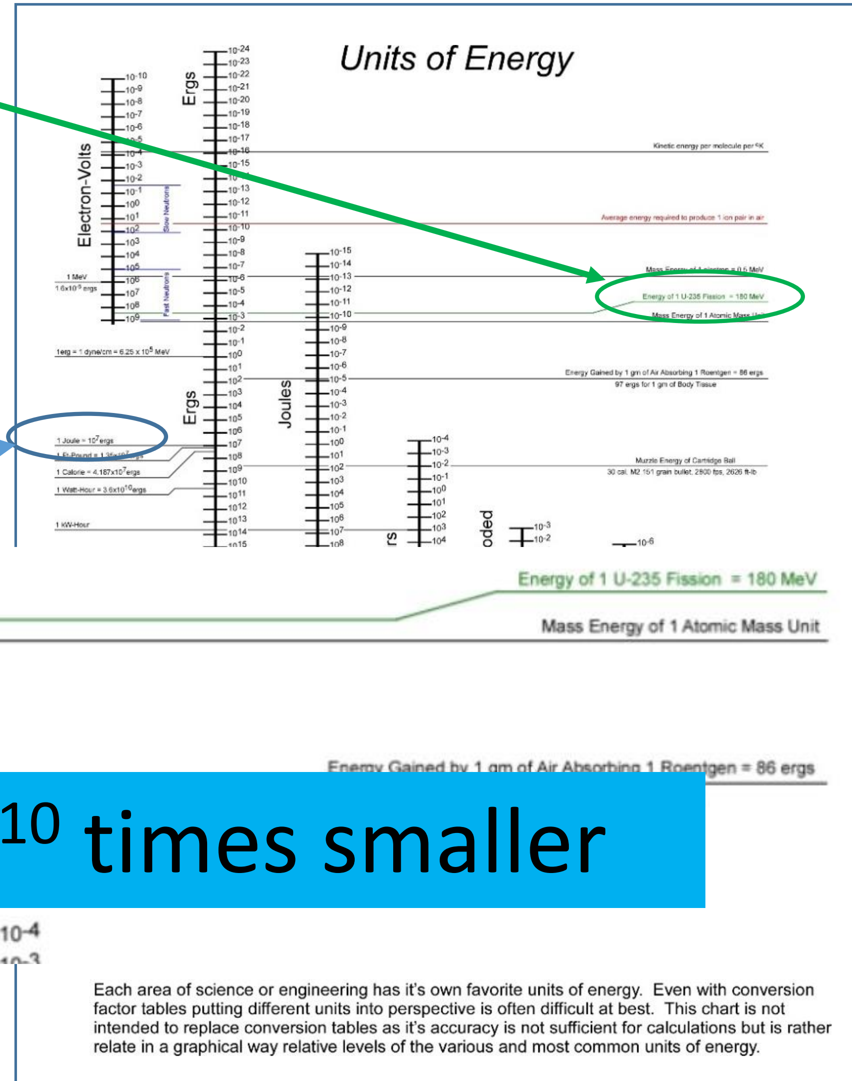
giving 234 x 8.53MeV /nucleon = ***1996 MeV***

so the change in binding energy is ***1996 – 1793.6 = 202.4 MeV***

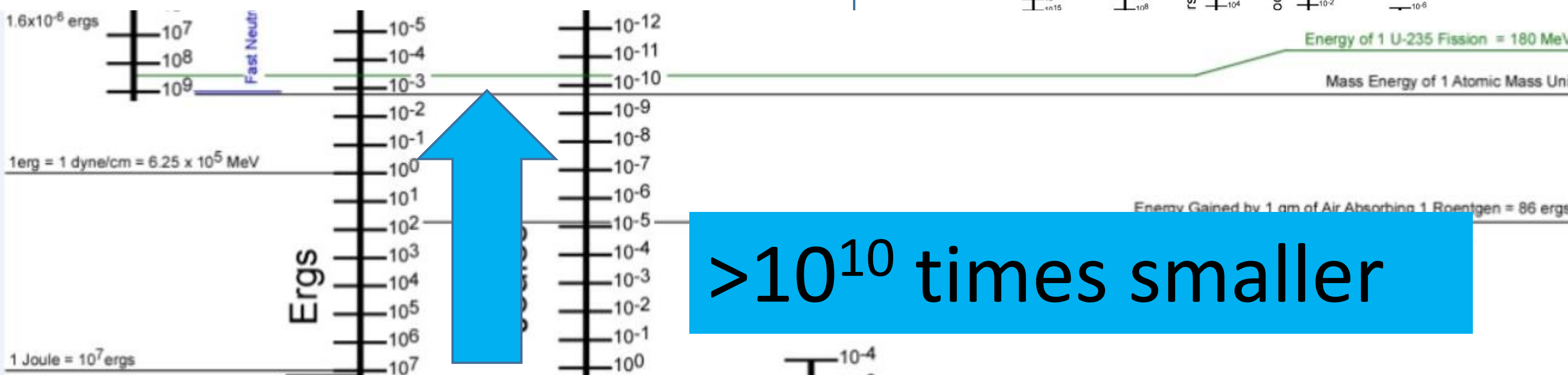
Energy released is equal to the change in binding energy

How Much is 200 MeV?

Fission of one atom of U235



Energy expended by one fun snap, about 1 Joule



$>10^{10}$ times smaller

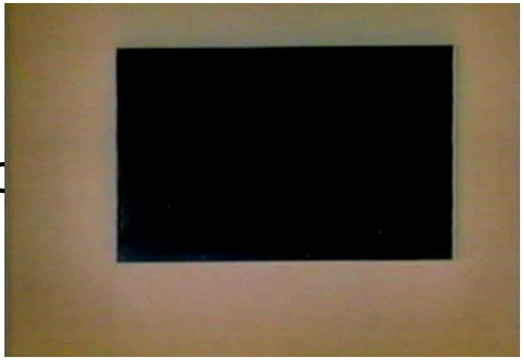
Criticality

- Is the measure of how the number of neutrons in a system change with time
- There are three conditions:

subcritical ~ neutron loss > neutron growth

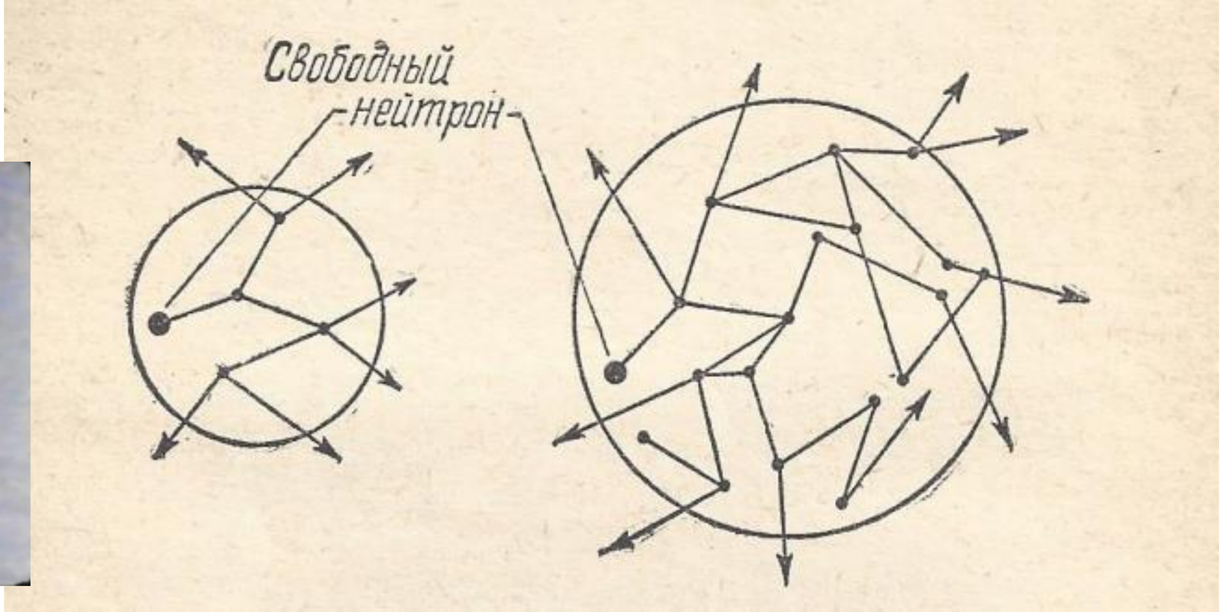
critical ~ neutron loss = neutron growth
or sustained chain reaction

supercritical ~ neutron growth > neutron
or a runaway chain reacti



Criticality and Geometry

- Volume and surface area determine critical mass
- Sphere is optimum
  but any geometry
  with a low surface
  area to volume
  ratio is acceptable



Geometry

- Shape

  Shapes with smaller surface area have smaller critical mass

- For a bare ^{235}U

Density = 18.8 g/cm^3
Mass = 100kg

Density = 18.8 g/cm^3
Mass = 52kg

Density

- Density

  Increasing the material density results in a smaller critical mass

- For a bare sphere of ^{235}U normal density

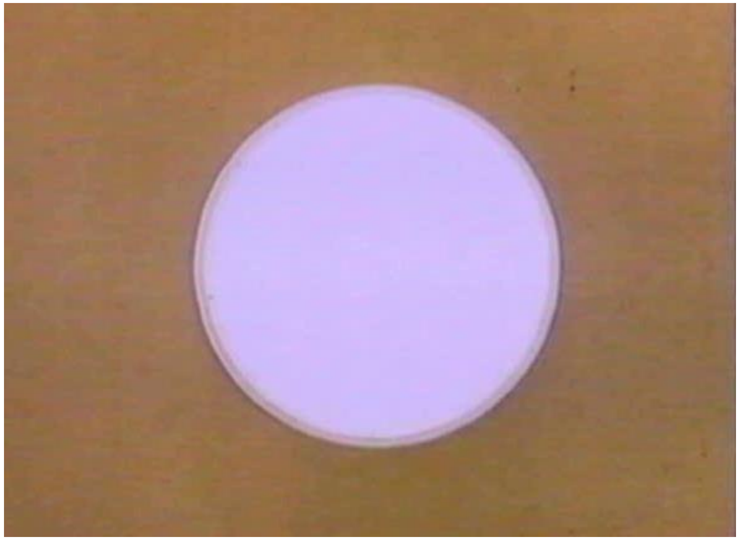
but $M_{crit} \approx R^3$

Density = 18.8 g/cm^3
Critical Mass = 52kg

Density = 37.6 g/cm^3
Critical Mass = 13kg

Super Criticality

- In a nuclear explosive device, we want to create far more neutrons than are lost
- This is a supercritical mass
- This is the basis of the atomic bomb



Nuclear Weapons Made Very Very Simple

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Creating a Super Critical Mass

- Change in geometry, the surface area
- Change in density
- Change in density and surface area
- Creating a supercritical mass is called - ***Assembly***

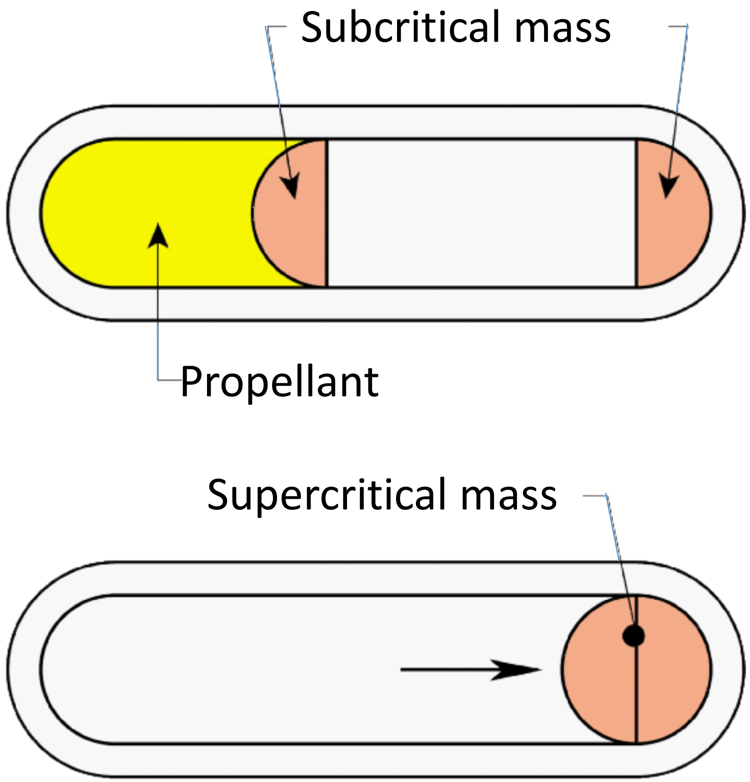
SO

Creating a Supercritical Explosive Device

- Two methods of assembly
- Physically assemble two subcritical masses such that the result is a supercritical mass,
  "the gun"
- Compress a subcritical mass to increase the density and reduce the surface area to a supercritical state,
  "the implosion"

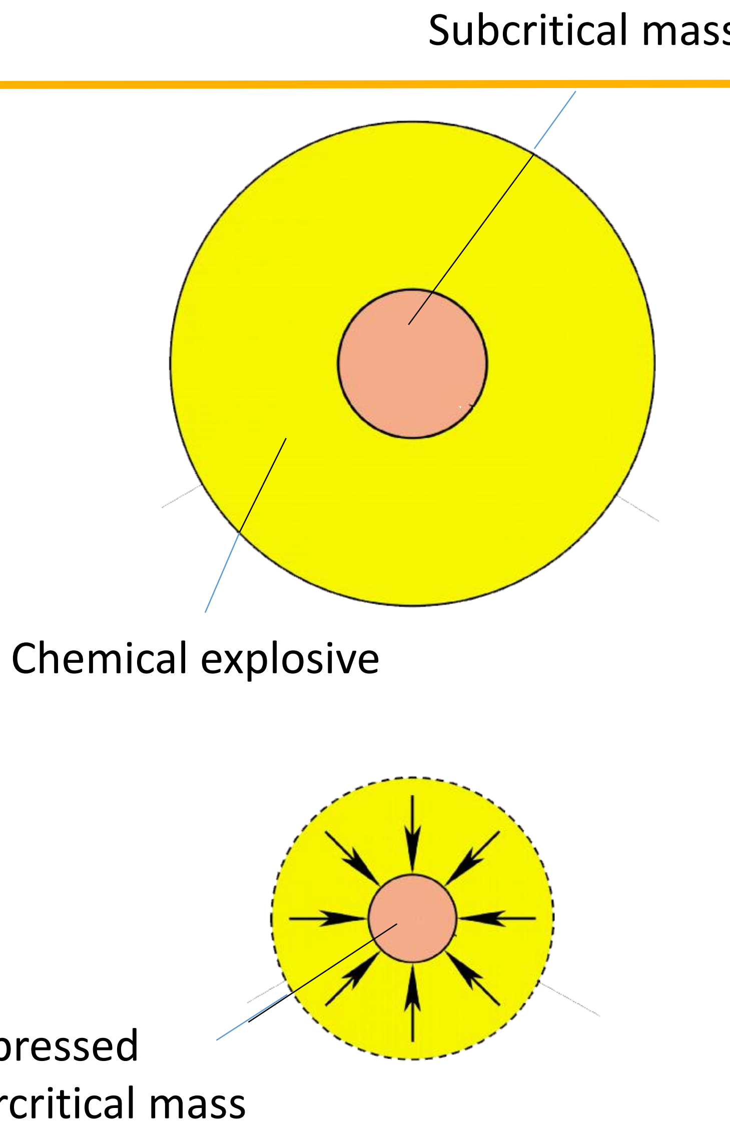
Gun Assembly

- Simple design
- Assemble the subcritical masses with a propellant, not explosive
- Very inefficient
- Assembly in milliseconds



Implosion Assembly

- Very difficult to build
- Requires symmetrical implosion from explosives to compress the fissile material known as the “***pit***”
- Much more efficient use of material than gun type
- Assembly in microseconds



Fission Weapons Basics

- You must

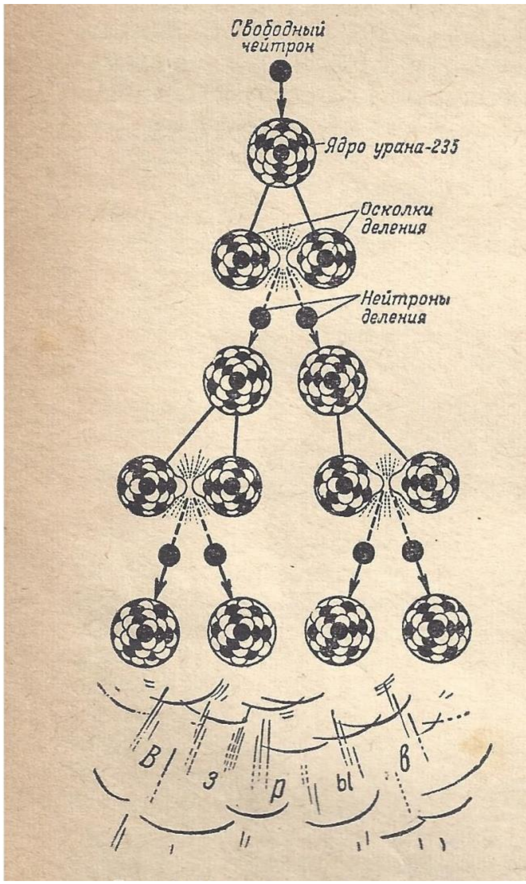
  Create or ***assemble***, a supercritical configuration of fissile material from a subcritical configuration

  Initiate a ***neutron chain reaction*** in the supercritical configuration at the optimum time to achieve desired explosive yield with a device called an ***"initiator".*** There are several ways to make modulated neutron sources

- You would like

  Maintain the supercritical configuration, hold it together, long enough to create a large release of energy, aka, ***tamping***.(LAUR-11-03126)

Chain Reaction



Atomic Weapons and Defense, Moscow, 1958

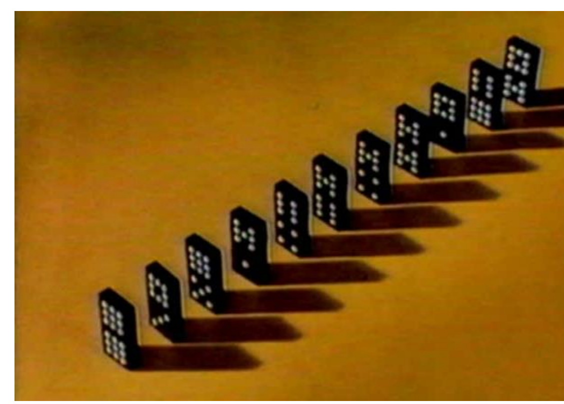
If the fission process continues it is called a "chain reaction."

Fissile Material, is a material that can sustain a chain reaction with neutrons of any energy, ie, thermal neutrons

Fissionable Material, is a nuclide that can undergo fission after capture of a neutron

^{235}U is fissile

^{238}U is fissionable



Initiation

- At the time of assembly, that is,

  for the gun, when the two masses are together

  for the implosion, when the material is at maximum density

- The chain reaction is started by bombarding the assembly with a neutron or better, many neutrons
- It is crucial to start the chain reaction at the optimum time to get maximum explosive yield
- A stray neutron or cosmic ray can start a chain reaction

  If a stray neutron shows up before the desired moment, this is known as ***preinitiation***

Both Assembly Methods have a Common Problem

- Initiating a supercritical mass can not be avoided
- At some point, a background neutron will start a chain reaction in a supercritical mass, neutrons come from

  Spontaneous fission of nuclear material

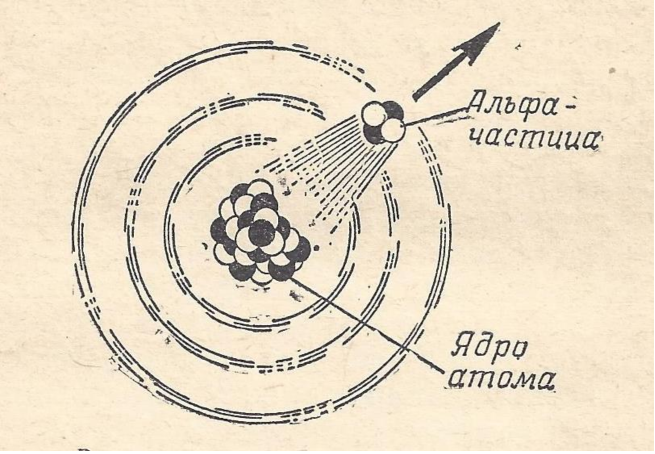
  Cosmic rays

  Alpha particle reaction with light elements, (α,n)

An example:

$^{238}U \rightarrow {}^{234}Th + \alpha$ (natural decay)

When an α particle interacts with a light element, such as Li, Be, B, C, O, F, Na, Mg, N, or Cl it ejects a neutron, which can start an unwanted chain reaction

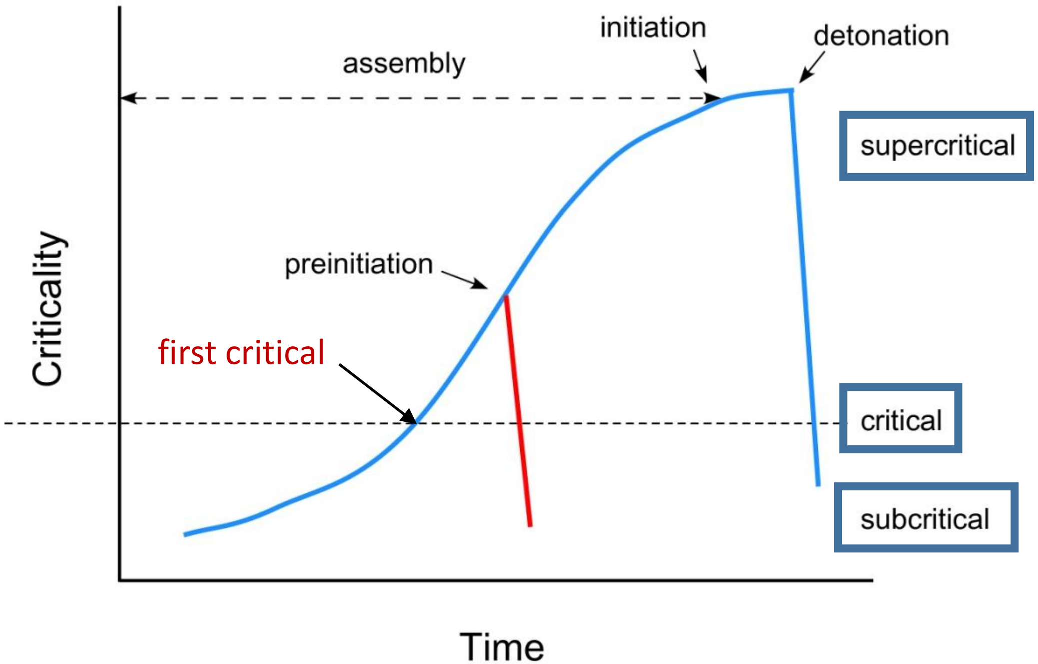


Preinitiation

During the assembly time, the device is susceptible to an early initiation from a stray neutron any time after first critical

This is called preinitiation and the results is a lower than desired device yield and is termed a *fizzle*

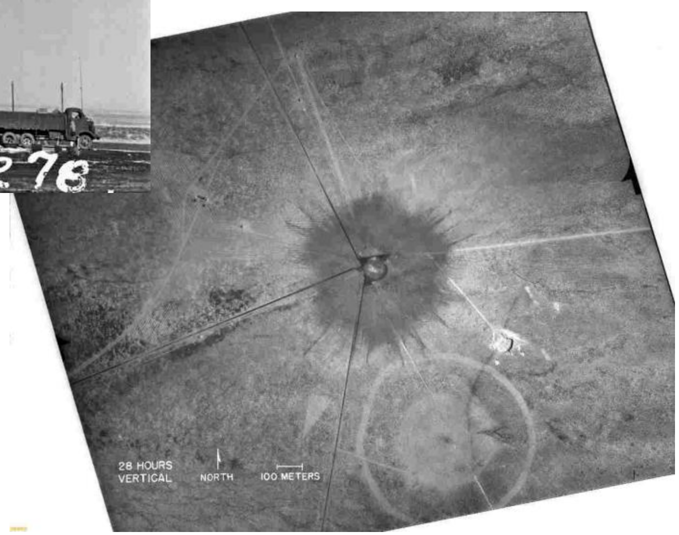
It's clear that the longer the assembly time the higher the probability of a fizzle



Natural neutron rates:
Oy ~ 1 Neutron/kg/sec
Pu ~ 60,000 Neutrons/kg/sec

Design Yield vs Fizzle Yield

Trinity
Big Smoking
Hole



Not so good
A "Fizzle"

Growth of Fission Chain Reaction

- The basis of the atomic bomb is to make as many neutrons (fissions) as possible as quickly as possible
- Neutron production >> neutron loss
  or, the number of neutrons (fissions) increases with time, the reaction is growing
- It grows exponentially, e^x

Exponential Growth

- The time from the creation of a fission neutron to its absorption in a subsequent fission event is called a ***generation***
- This time is about $\sim$ *10^{-8} sec and is known as a **shake***
- The number of, N, neutrons (or fissions) at generation "n" is

$$N_n = N_{intitial}\, e^n$$

The Effects of Nuclear Weapons, Glasstone, 1977

Exponential Growth is Very Rapid

N = # of fissions
n = # of generations

n	Time, us	Fissions, N_n	Energy , kT
50	0.5	5.2×10^{21}	0.04
55	0.55	7.7×10^{23}	5.3
60	0.6	1.1×10^{26}	787

$$N_n = N_{intitial}\, e^n$$

The Effects of Nuclear Weapons, Glasstone, 1977

Exponential Growth is Very Rapid

- Remember we mentioned ***tamping,*** holding the ***assembly*** together for just another microsecond ?

n	Time, us	Fissions, N_n	Energy , kT
50	0.5	5.2×10^{21}	0.04
55	0.55	7.7×10^{23}	5.3
60	0.6	1.1×10^{26}	787

99.9 % of the fission energy is released in the last 7 generations of a chain reaction

The Effects of Nuclear Weapons, Glasstone, 1977

Energy Released from a Nuclear Detonation

- Kinetic energy of fission fragments, 85%
- Electromagnetic energy
  - Gamma rays
  - X-rays
  - Electromagnetic
- Neutrons

Nuclear Weapons Made Very Very Simple

- Topics to be covered:
- Nuclear Physics
- Fission Weapons Basics
- **Materials**
- Thermonuclear Reactions
- The First Weapons Development
- Current Weapons

Materials

- Up to now, we've concentrated on ^{235}U
- Any material that can be configured into a supercritical mass and support a neutron chain reaction is suitable for atom bombs.
- The most popular being ^{235}U and ^{239}Pu

Production Plutonium

- ^{239}Pu is produced at a much higher rate in a reactor
- The large neutron flux also creates ^{240}Pu due to neutron capture of ^{239}Pu (good stuff)
- ^{240}Pu has a very large spontaneous fission rate, thus a lot of stray neutrons (bad stuff)

$$^{238}_{92}\mathrm{U} + \mathrm{n} \rightarrow {}^{239}_{92}\mathrm{U} \xrightarrow{\beta} {}^{239}_{93}\mathrm{Np} \xrightarrow{\beta} {}^{239}_{94}\mathrm{Pu}$$

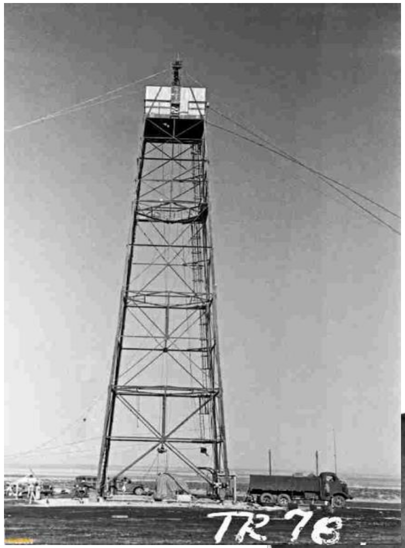
$T_{1/2}$ 24 $minutes$ $T_{1/2}$ 2.4 $days$ $T_{1/2}$ 24110 $years$

$$^{239}_{94}\mathrm{Pu} + \mathrm{n} \rightarrow {}^{240}_{94}\mathrm{Pu}$$

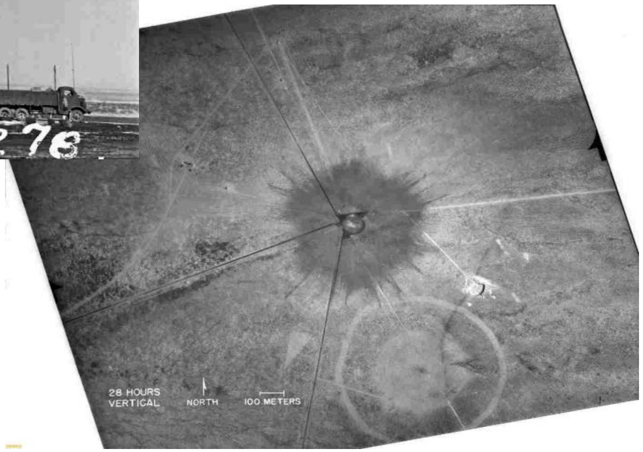
$T_{1/2}$ 6353 $years$

Neutron background rate
^{240}Pu ~ 920,000 n/kg/sec

Remember Preinitiation?



Trinity
Big Smoking
Hole



Stray neutrons are bad

Uranium Enrichment

- About 0.7% of natural uranium is ^{235}U so all that is required is to separate the ^{235}U from the ^{238}U.

- Electromagnetic separation using calutrons, (California-Uranium-tron) which is basically a mass spectrograph designed for production.

- Gaseous diffusion at the K-25 (derived from Kellex Corp plus 25 the code name for 235U)

Plutonium Production

- Plutonium was produced at Oak Ridge X-10 reactor seen here in November 1943

- B Reactor at Hanford in operation in September 1944

How Much Material

- For a gun device, it's quite obvious you need more than a critical mass. From the chart we get about 50kg of "weapons grade uranium".
- For an implosion device you need slightly less than a critical mass. Again from the chart we need less than about 10kg of weapons grade plutonium.
- Hypothetically, a mass of 4 kilograms of plutonium or uranium-233 is sufficient for one nuclear explosive device. (94-1)
- Hypothetically, a mass of 25 kilograms of ^{235}U is sufficient for one nuclear explosive device. (LAUR-11-03126)

Special Nuclear Materials

From LAUR-05-7078	**Density**	**Critical Mass**	**N Rate**	**Heat**
Mat'l	**g-cm^{-3}**	**kg**	**n-kg^{-1}-s^{-1}**	**W-kg^{-1}**
			q	*H*
"^{233}U"	18.60	17.1	1.2	0.3
Oy-97	18.80	49.0	0.5	0.003
Oy	18.80	53.6	1.1	0.002
Oy-37	18.90	248	8.6	0.001
Tu	18.98		14	Nil
^{237}Np	20.40	58.8	0.14	0.02
"^{238}Pu"	19.43	10.5	2.1×10^6	443
Tengen Pu	19.50	10.4	3.6×10^3	2.3
2% αPu	19.50	10.6	2.0×10^4	2.0
6% αPu	19.50	10.9	5.9×10^4	2.2
6% δPu	15.80	16.9	5.9×10^4	2.2
LWR αPu	19.54	14.2	4.1×10^3	13(21)
"^{242}Pu"	19.70	64.1	1.6×10^6	5.4
Am	13.50	69.0	1.1×10^3	91.5

Why Pu?

- Pu is a very cumbersome material to handle
- It’s expensive and complicated to make
- It has many undesirable properties like being very pyrophoric and reacting with most everything
- It oxidizes and hydrides readily and it’s very toxic being a heavy metal

Why Pu?

	Neutron Energy		
Nuclide	~0 MeV	0.5 MeV	14 Mev
U -235	2.43	2.49	4.1
Pu- 239	2.80	2.85	4.9

Fission Neutron Energy

If you want to build a nuclear stockpile, it's very convenient to have a fissile material you can make.

Nuclear Weapons Made Very Very Simple

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Fusion Reaction

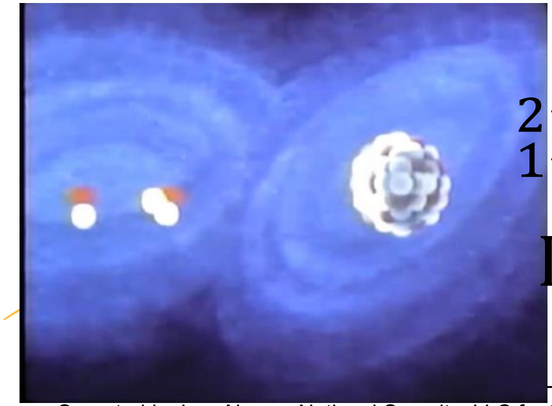
- The lowest temperature thermonuclear reaction is deuterium and tritium at about 5 million degrees

$$ {}^{3}_{1}\mathrm{H} + {}^{2}_{1}\mathrm{H} \rightarrow {}^{4}_{2}\mathrm{He} + \mathrm{n} $$

$$ \mathrm{T} + \quad \mathrm{D} \rightarrow {}^{4}_{2}\mathrm{He} + \mathrm{n} $$

17.6 MeV released

- All other thermonuclear reaction are much higher temperature such as:



$$ {}^{2}_{1}\mathrm{H} + {}^{2}_{1}\mathrm{H} \rightarrow {}^{3}_{2}\mathrm{He} + \mathrm{n} $$

$$ \mathrm{D} + \quad \mathrm{D} \rightarrow {}^{3}_{2}\mathrm{He} + \mathrm{n} $$

3.2 MeV released

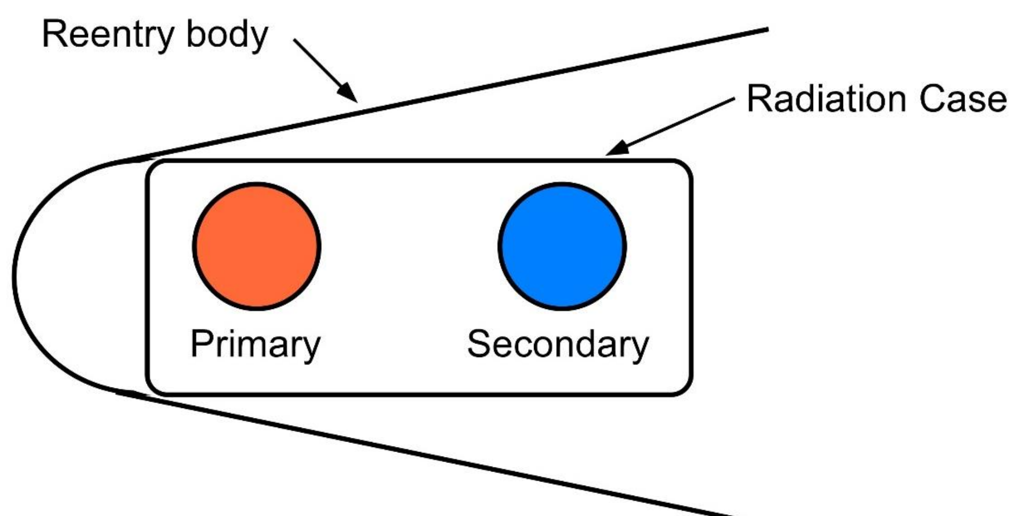
Fission Primaries, “Boosting”

- Boosting refers to the use of DT fus
enhance the fission chain reaction t
efficiency of the primary in generat
- A mixture of deuterium and tritium, called the boost gas, is introduced into a hollow pit
- During implosion the boost gas is compressed
- Driven by energy from the fission reaction, a DT fusion reaction occurs making copious high energy neutrons that in turn trigger more fission reactions, thus making a very efficient primary


THE
THERMONUCLEAR
WEAPON
PART VI

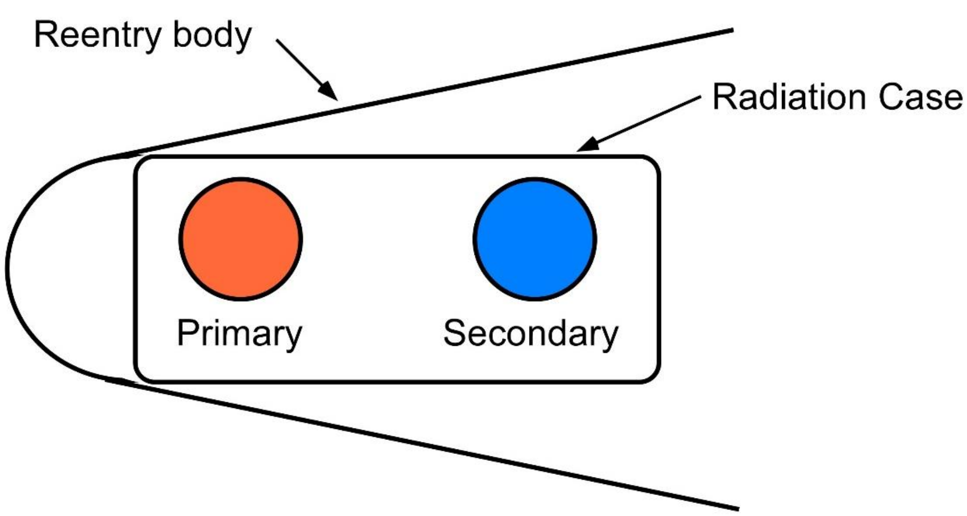
Thermonuclear Staged Weapon

- Adding another stage, ***the secondary***, to an atomic weapon can greatly boost the yield
- The secondary stage can contain:
- Thermonuclear fuel in the form of liquid or gaseous D and T or lithium deuteride, LiD, and fissionable material



Staged Weapons

- X-rays produced by the primary fission stage is contained by the radiation case
- The "rad" case is made of a material opaque to x-rays
- X-ray energy flows toward the and around the secondary, heating and compressing it



Radiation Coupling

- Radiation coupling refers to the use of x-rays from a fission primary to transport energy for compressing the secondary
- In an two-stage weapon the primary must be an effective source of radiation, that is, it must high efficiency.
- A high efficient x-ray source requires that a large amount of energy is deposited in a small mass
- As mentions previously, this is accomplished with boosting of the primary

Fusion Fuel

- Heating and compression liquid or gaseous DT to a sufficiently high temperature, about 5 million degrees results in a fusion reactions releasing copious high energy neutrons, 14 MeV.
- With LiD fuel there is another step in the process, while undergoing heating and compression in the secondary, the fuel reacts with neutrons from the primary creating tritium, which in turn reacts with the deuterium creating high energy neutrons thus
- LiD is a convenient way so store tritium without the persistent problem of short half-life

The Next Section is Optional

- Continue to next slide to include the first atomic weapons FM and LB
- OR hide slide 56 thru 75 to omit LB and FM
- Skip to slide 76

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- Materials
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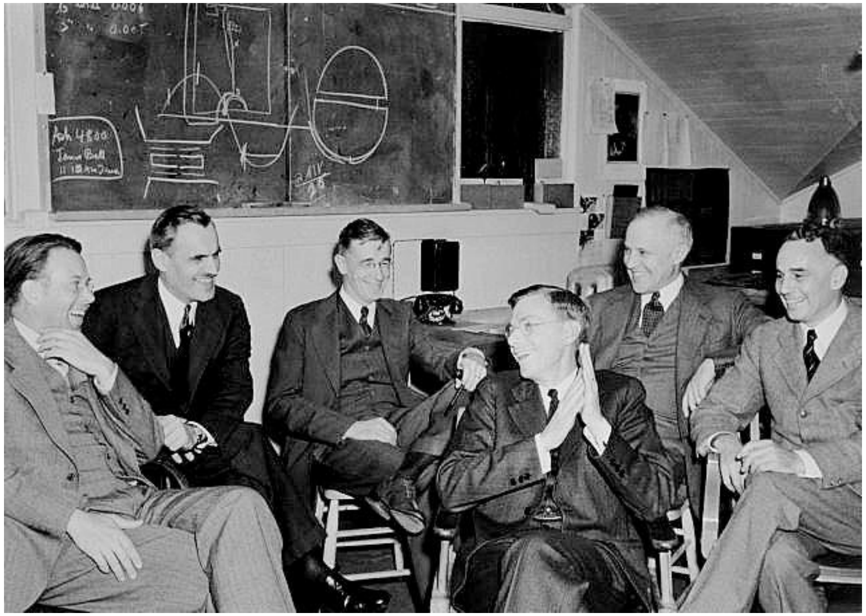
- **The First Weapons Development**
- Current Weapons

Berkeley July 1942

- Hans Bethe, James Conant, John Van Vleck, Edward Teller, Emil Konopinski, Robert Serber, Stan Frankel, Eldred C. Nelson, Felix Bloch, Emilio Segrè, John Manley and Edwin McMillan met to develop concepts for a fission weapon.

- Decided on two designs to create a supercritical configuration

- ***BOTH Using Plutonium***



The First Plutonium

- ^{239}Pu was first produced using the Berkeley cyclotron in February 1941
- This was accomplished by irradiating ^{238}U with deuterons with very low neutron flux
- About 1ug was produced

$$^{238}_{92}\mathrm{U} + ^{2}_{1}\mathrm{H} \rightarrow \mathrm{n} + ^{239}_{93}\mathrm{Np} \rightarrow ^{239}_{94}\mathrm{Pu}$$

$$T_{1/2}$$
$$2.4\ days$$

Summer of 44

- To make a long story short, Enrico prediction about Pu made in a reactor came true.
- The Pu240 content in the Pu from the X-10 reactor at Oak Ridge resulted in such a high spontaneous fission rate too high to be used in a gun assembly.
- Someone now must tell Gen. Groves (soon to be Pvt. Groves) he just spent $2 billion dollars on reactors at Hanford and we can't use Pu.
- Three important things happened,

  One, the Pu gun program was terminated over about a two week period and Uranium was now the material of favor

  In this same period, almost the entire "lab" was reorganized around the implosion concept

  Seth Neddermeyer, chief proponent and head of the implosion group since 1942, was fired, and George Kistiakowsky was put in charge of implosion. *Thank you Seth!*

Ending the War

Fat Man

Thin Man

Bad Man

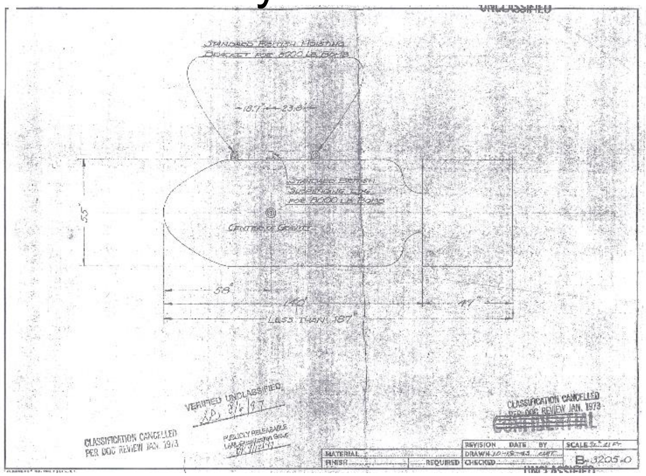
Both Were Plutonium Bombs

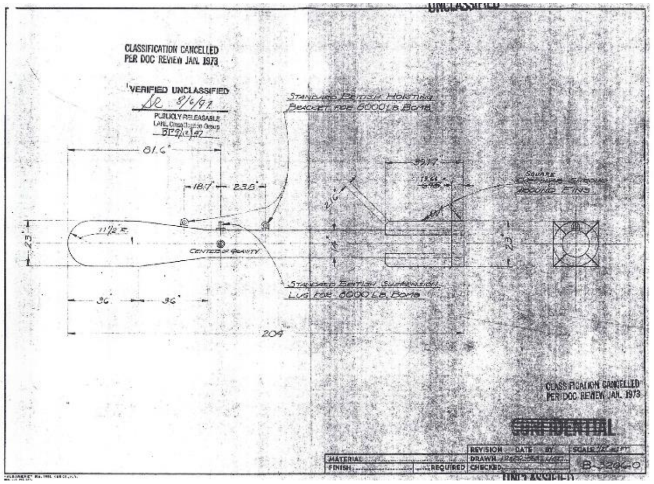
Thin Man and Fat Man (aka Pumpkins) Drop Cases at Wendover Field

Who Named the Bombs?

- November 29, 1944, Col. D.L. Putt, Technical Staff, Bombardment Branch, Engineering Division, Wright Field, informed Gen, L. Groves and Norman Ramsey the Air Corps had designated to two bomb concepts as “*Fat Man*” and “*Thin Man*”
- This was done for security concerns because of the increased communications with the Boeing about the “Pullman” aircraft.
- Referenced to the Pullman Palace Car Co. makers of fine rail cars

The “Stubby” Bomb

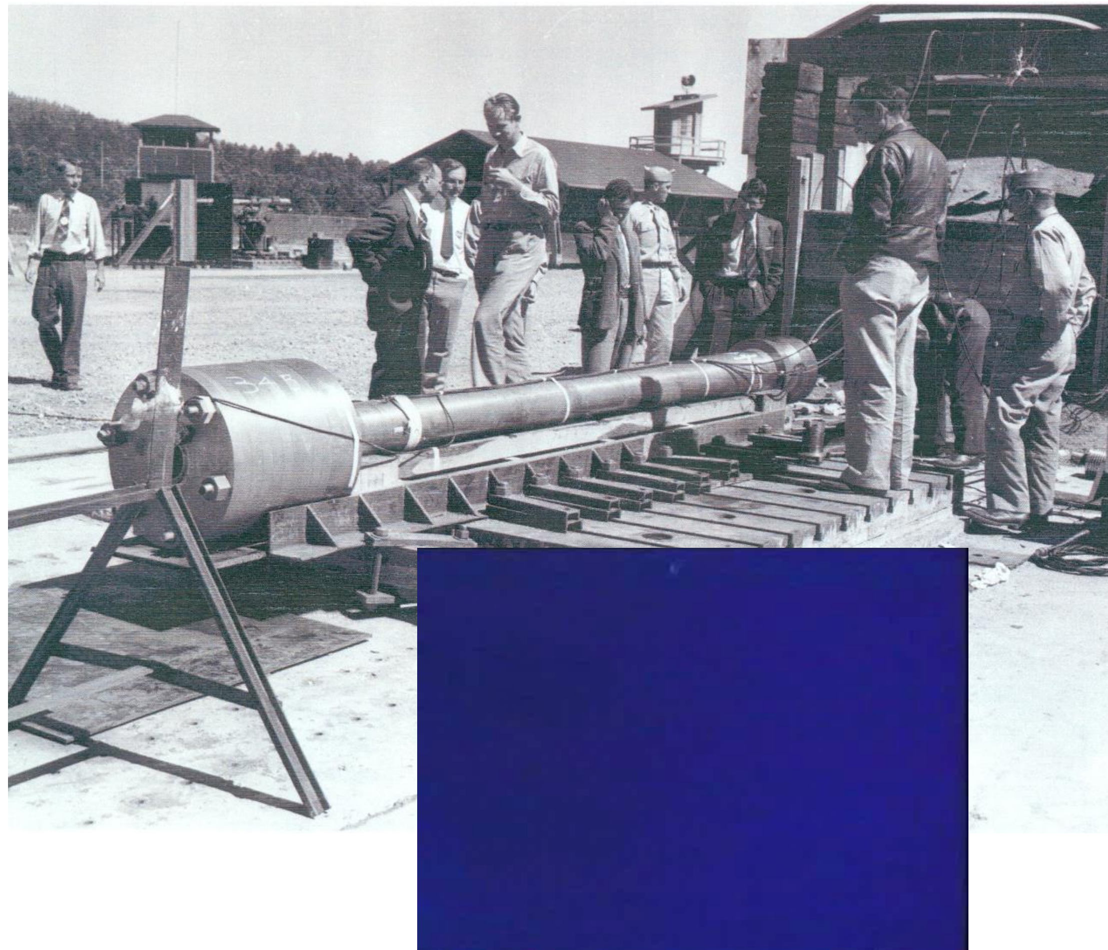




The “Long” Bomb

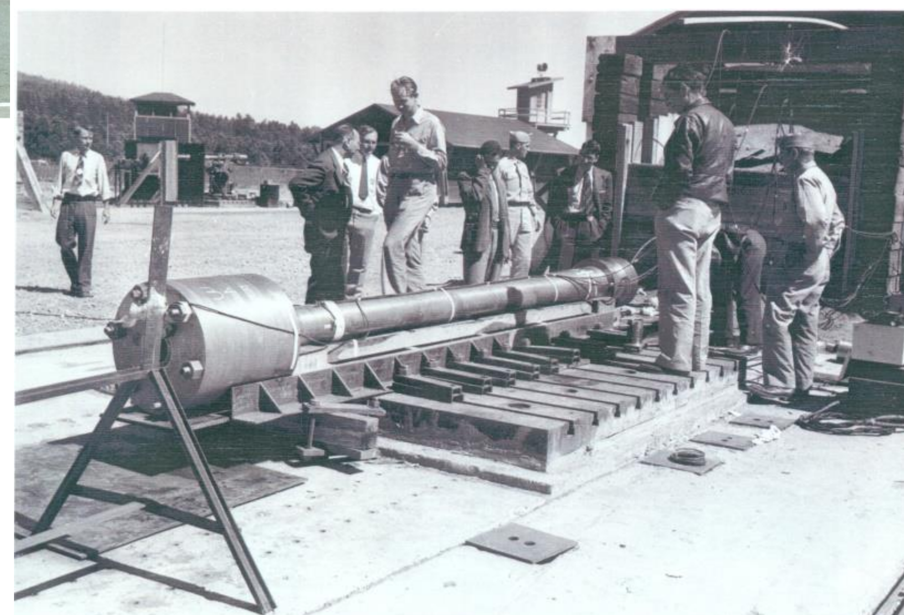
The 1st Gun Assembly

- Thin Man
- Was a Pu gun
- Assembly occurs in milliseconds
- Los Alamos was a very busy place



Thin Man

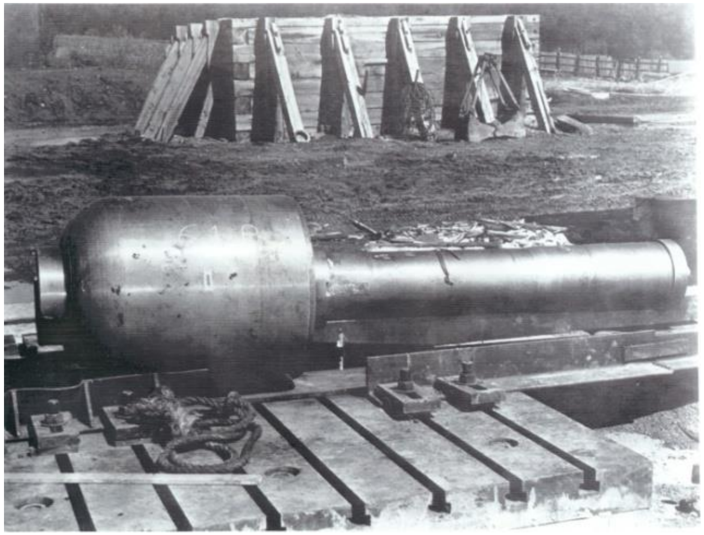
- Thin had a problem



- First samples Pu samples from the X-10 reactor were received in April 1944

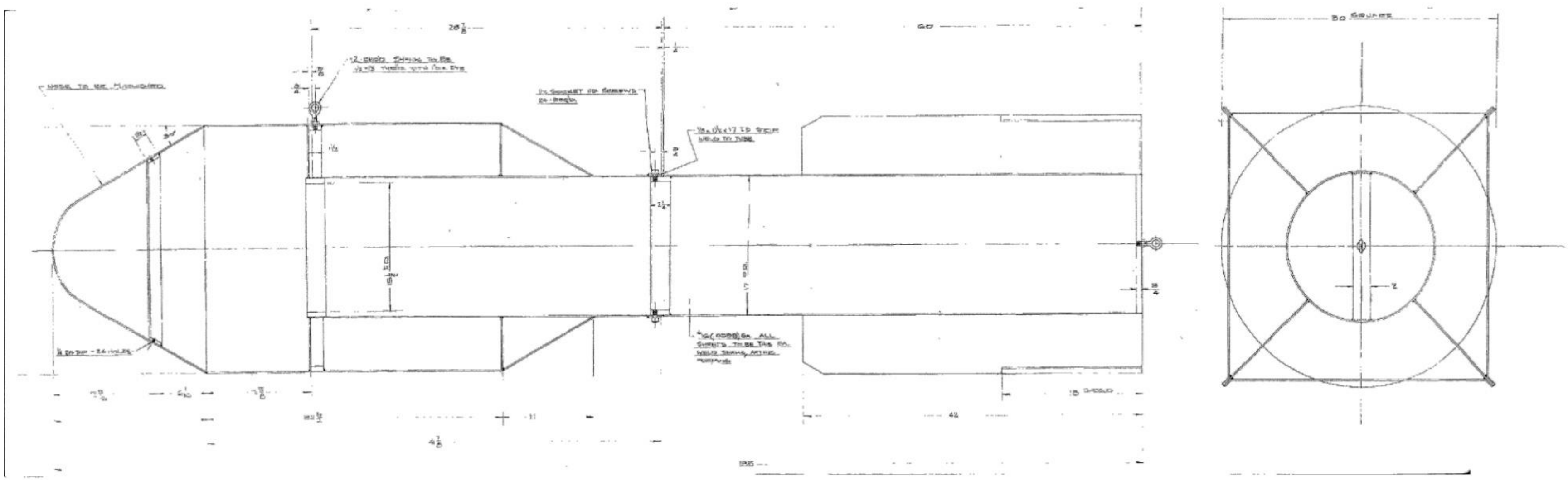
Thin Man became Little Boy

- When Emilio Sergre confirmed in the summer of 1944 that the spontaneous fission rate of reactor created Pu was to great to use in a gun weapon the program was halted.
- Uranium was now the material of choice for the gun program and presented little technical problems.
- Thin Man (17 feet) became Little Boy (10 feet)
- ***But***



Middle Man?

- Somewhere between Thin Man and Little Boy

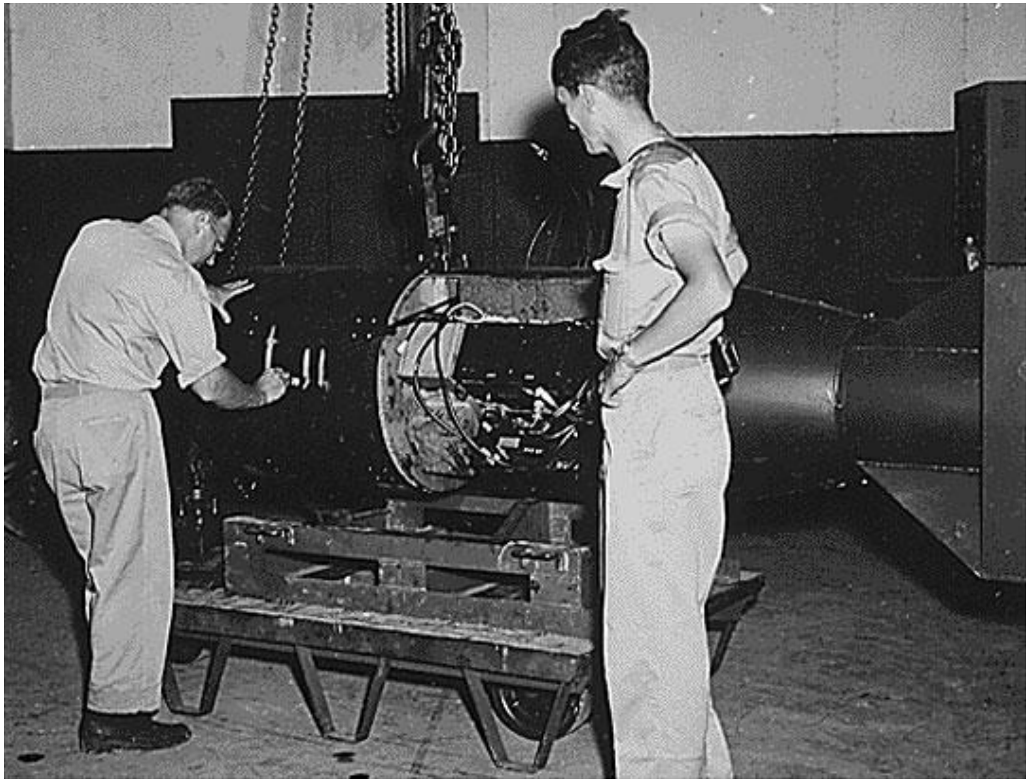


TOLERANCE ± 010 UNLESS OTHERWISE NOTED			REV LET	CHANGED ITEM WAS	DATE
LAYOUT OR SKETCH BY		DATE	PART NAME		
DRAWN BY	T.E.F.	5-18-44	MIDDLE MAN SHELL		
CHECK BY					
GROUP REPR.	GR. NO. E 3		SCALE 1/4	DRAWING NO.	
CH. ENG.			SHT. # 1	D1300E-1A	
APPROVED			1 SHTS.		

Little Boy

- Detonated 1900 ft above Hiroshima 6 Aug 1945
- Used Navy Mk 15 electric primer (16” bag guns)
- Used ^{235}U
- Yield

  15kT(lanl.gov)
- Yield measured in combat, but that’s another story



Hiroshima 8:20 AM
6 Aug 1945

Implosion was not so simple

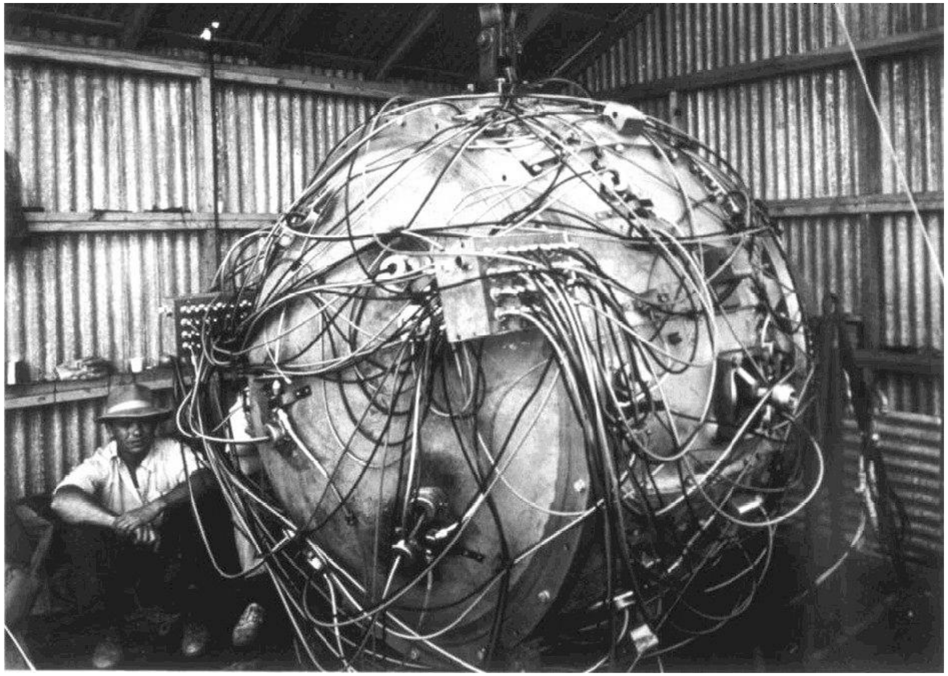
- With the Pu gun program terminated and the uranium gun well in hand the focus was shifted to the implosion design.
- If an implosion device could not be perfected then Pu was of no use and the millions of dollars spent at Oak Ridge and Hanford was all for naught.
- Intense effort was now focused on the implosion “gadget”. The lab grew from 1000 to over 2500 in a year.
- This device was so complex. it had to be tested.

The Implosion Design

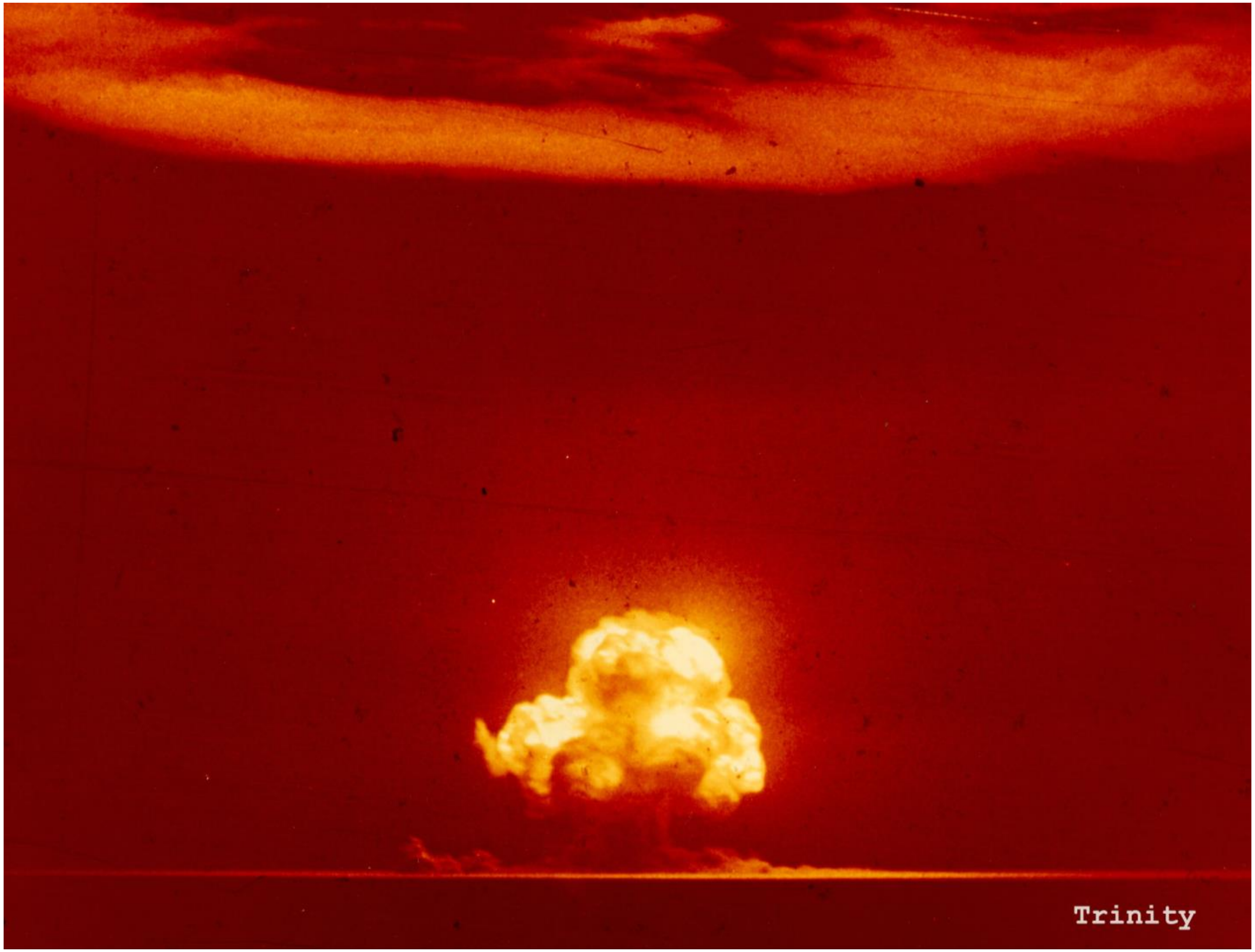
- Firing system
- Detonators
- High explosive lenses
- Main HE charge
- Pit containing fissile material
- Neutron initiation source
- Thousands of parts!!!

Trinity, the Test of Implosion

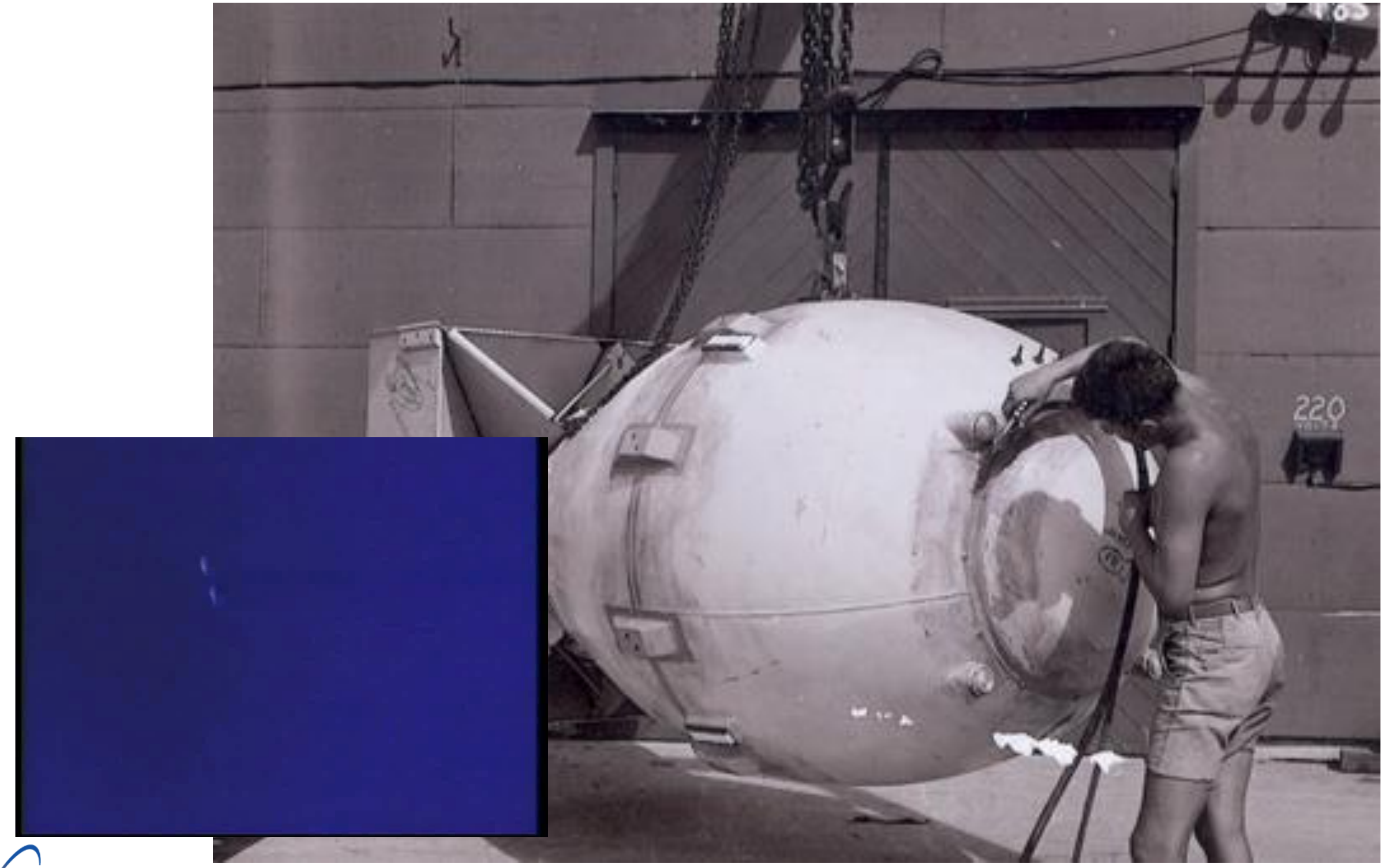
- Detonated atop 100 ft tower on 16 July 1945(48-2)
- Used 13 ½ lbs of Pu (53-1)(00-1)
- 32 detonators each having two bridge wires(00-1)
- Yield
  - 20kT(53-1)
  - 21kT(lanl.gov)
  - 18.6kT(DOE/MA-0001)



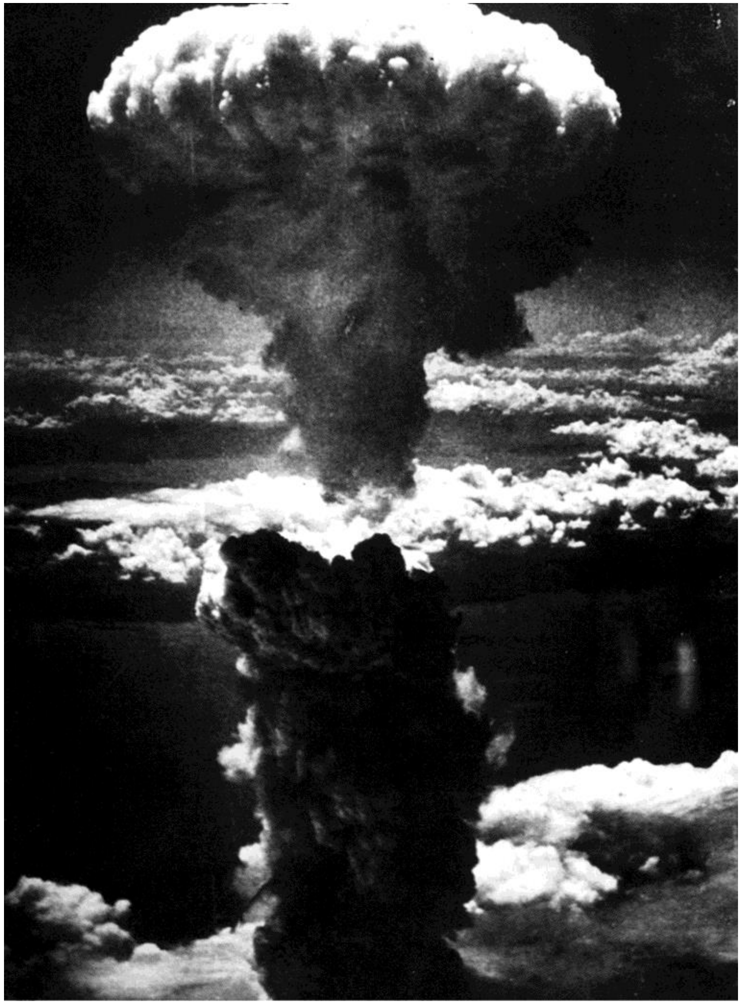
16 July 1945



Fat Man



Nagasaki 11:02 AM
9 Aug 1945



Japan surrendered the next day

Nuclear Weapons Made Very Very Simple

- Topics to be covered:
- Nuclear Physics
- Fission Weapons Basics
- Materials
- Thermonuclear Reactions
- **Current Stockpile**

The Next 45 Years

- The U.S. fielded 65 nuclear weapons systems of over 100 design concepts
- 59 of these have been retried
- The enduring stockpile consists of the:

B61
W76
W78
W80*
W88

los alamos
scientific laboratory
of the University of California

Los Alamos
NATIONAL LABORATORY
EST. 1943

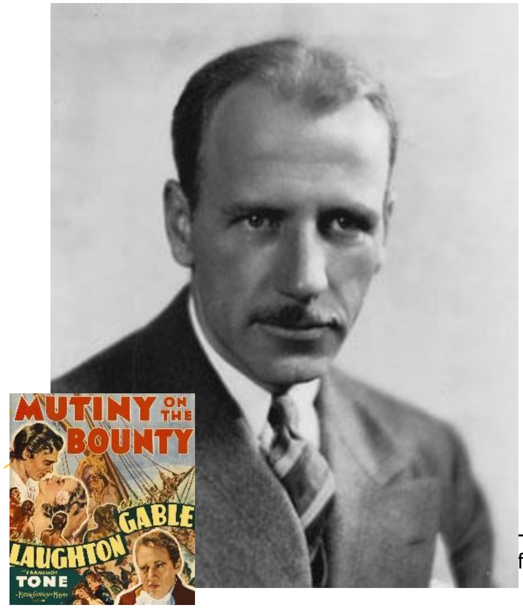
- W87
- B83

*Transferred to LLNL in 2001


Nuclear Weapons
of the United States
In 45 Seconds


TRIDENT II FIRST FLIGHT
Los Alamos National Laboratory/Sandia National Laboratory/Naval Weapons Center

Special Thanks to Our Q-Cleared Narrators



Discussion and Questions